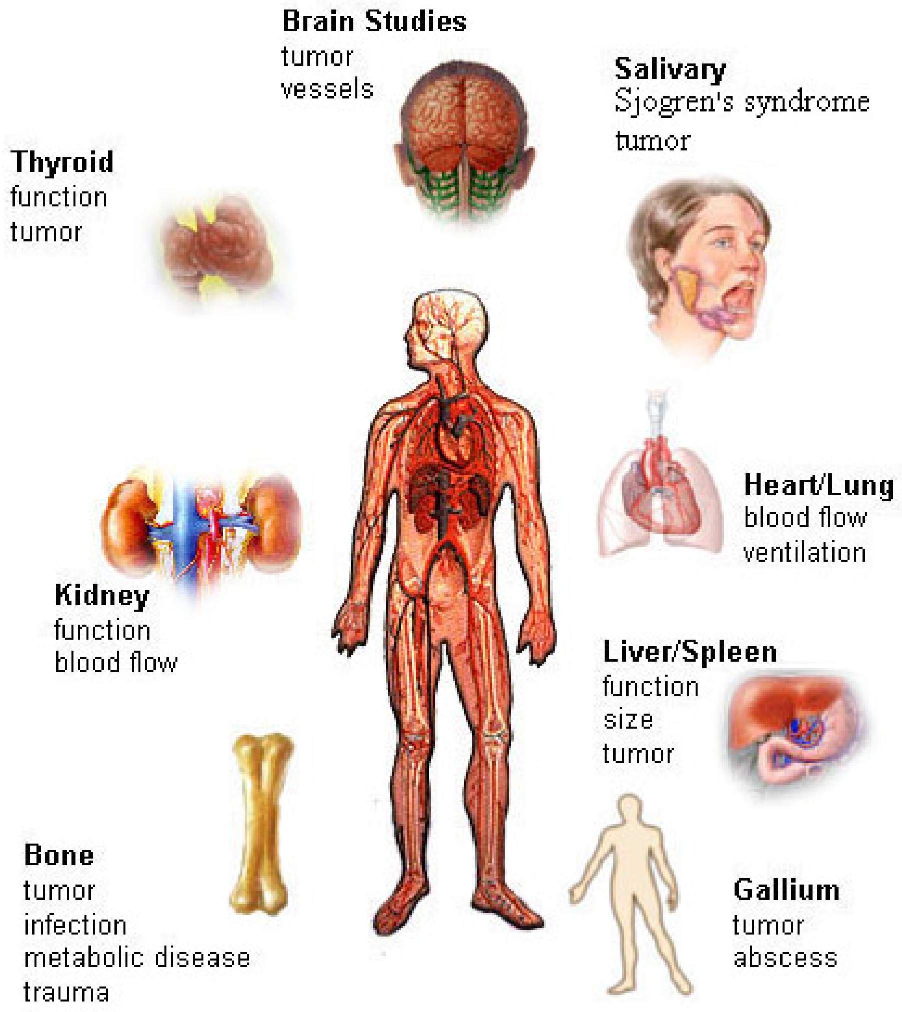
Physics of Nuclear Medicine



DIAGNOSTIC IMAGING - NUCLEAR MEDICINE

Physics of Nuclear Medicine

Radiation

* **Non-ionizing radiation** cannot ionize matter because its energy per quantum is below the ionization potential of atoms. Near ultraviolet radiation, visible light, infrared photons, microwaves and radio waves are examples of non-ionizing radiation.

* **Ionizing radiation** can ionize matter either directly or indirectly because its quantum energy exceeds the ionization potential of atoms. X rays, γ rays, energetic neutrons, electrons, protons and heavier particles are examples of ionizing radiation.

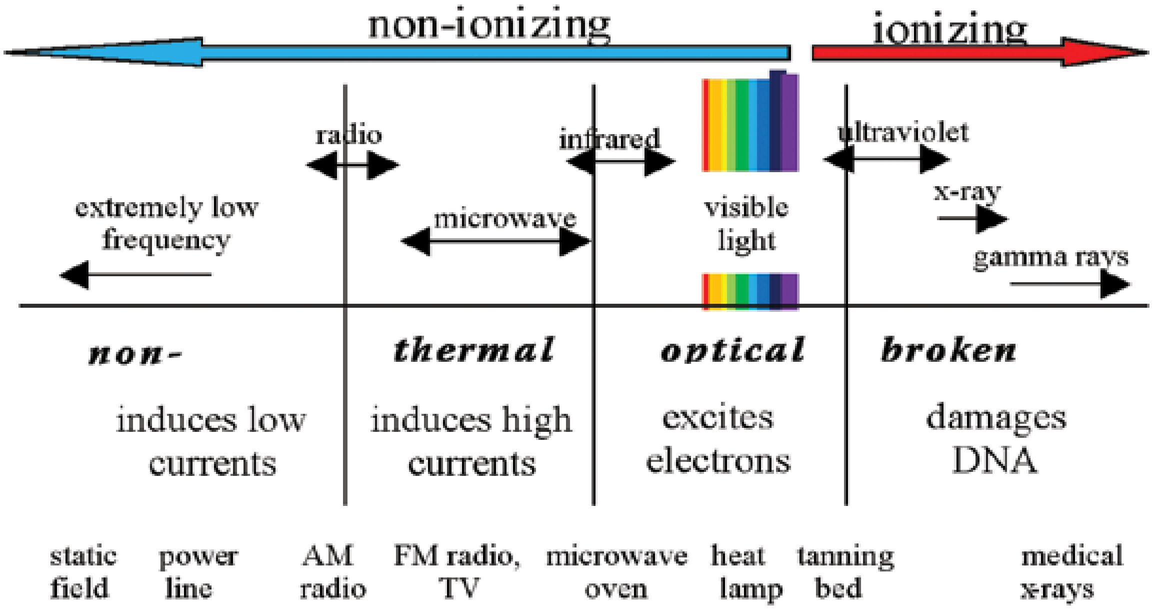


Fig. 1. Classification of Radiation

Nuclear transformations are usually accompaniedمصحوبه by emission of energetic particles (charged particles, neutral particles, photons, etc.). The particles released in the various decay modes are as follows:

1- Alpha particles in α decay;

In alpha decay, the nucleus emits an alpha particle; an alpha particle is essentially a helium nucleus, so it's a group of two protons and two neutrons. A helium nucleus is very stable.

An example of an alpha decay involves uranium-238:

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

2- Electrons in β – decay;

A beta particle is often an electron, but can also be a positron, a positively-charged particle that is the anti-matter equivalent of the electron. If an electron is involved, the number of neutrons in the nucleus decreases by one and the number of protons increases by one. An example of such a process is:

$$^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$$

3- Positrons in β+ decay;

4-Neutrinos in β+ decay;

5- Antineutrinos in β– decay;

6- Gamma rays in γ decay;

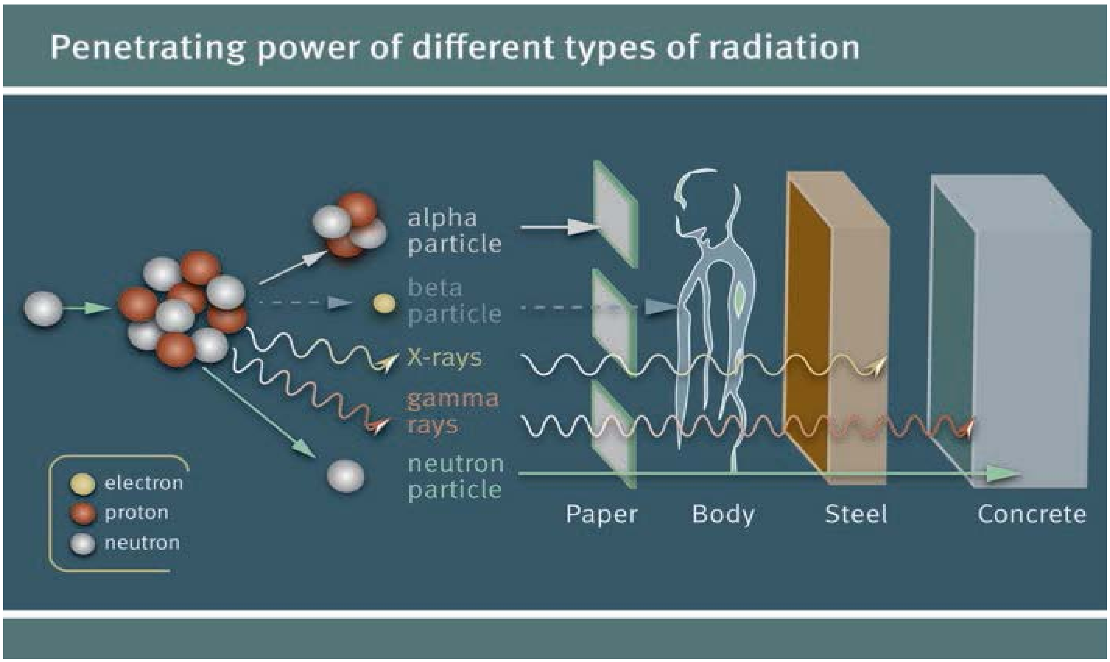
The third class of radioactive decay is gamma decay, in which the nucleus changes from a higher-level energy state to a lower level. Similar to the energy levels for electrons in the atom, the nucleus has energy levels. The concepts of shells, and more stable nuclei having filled shells, apply to the nucleus as well. Gamma rays are very penetrating; they can be most efficiently absorbed by a relatively thick layer of high-density material such as lead.

7- X- rays;

8- Neutrons in spontaneous fission and in neutron emission decay;

9- Heavier nuclei in spontaneous fission like alpha particle ;

10- Protons in proton emission decay.



Radioactive Decay

Many nuclei are radioactive. This means they are unstable, and will eventually decay by emitting a particle, transforming the nucleus into another nucleus, or into a lower energy state. A chain of decays takes place until a stable nucleus is reached..

$(dN / dt) \alpha$ number of total radioactive atom.

... $dN/dt = -\lambda N$

$dN/N = -\lambda\, dt$

$N = No\, e^{-\lambda t}$ (1)

N = Number of Radioactive Atoms after t = time

No = Number of Radioactive Atoms at t = 0(original number)

λ = decay constant , unit ($sec.^{-1}$, $min.^{-1}$)

e = Natural logarithm (2.718)

from equation (1):

$dN/dt = (dN_o/dt) * e^{-\lambda t}$

Since,

$dN_0/dt = A_0$

$A_0 = \lambda N_o$ (activity of atoms at $t = 0$).

and,

$- dN/dt = A = \lambda N$ (activity of atoms at t)

To calculate the radioactivity at any time t :

$$A = A_o e^{-\lambda t} \qquad (2)$$

The Half-Life is defined as the time elapsedمنقضي when the intensity of the radiation is reduced to one half of its original value.

$(T_{1/2})_{Phy.}$: ***(physical half life time***) is the time required for either the number of radioactive atoms or the activity reduce to half of its original value.

At time , $t = (T_{1/2})$ Phy ,

$N = (1/2) No$ and $A = (1/2) Ao$

Substituted this condition in equation (1):

$N/No = (1/2) = e^{- \lambda T1/2}$

$1/2 = e^{- \lambda T1/2}$

By taking , in, of both sides of equation we get:

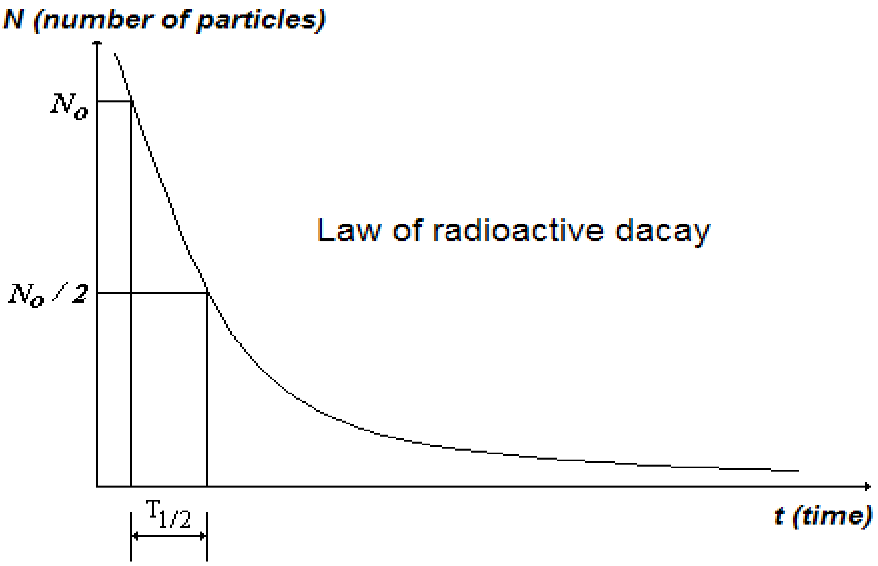
$\ln (1) - \ln (2) = - \lambda T_{1/2}$

$0.693 = \lambda T_{1/2}$

$$T_{1/2} = 0.693 / \lambda \qquad (3)$$

or,

$$\lambda = 0.693 / T_{1/2} \qquad (4)$$



Note: In equations 1.2,3,4 the unit of time and decay constant must be **, t** (sec) , **λ** (sec^{-1}) , **t** (min), **λ** (min^{-1}).

Average Life (Mean Life)

The actual lifetimes of individual radioactive atoms in a sample range anywhere from “very short” to “very long.” Some atoms decay almost immediately, whereas a few do not decay for a relatively long time. The average lifetime T_a of the atoms in a sample has a value that is characteristic of the nuclide and is related to the decay constant λ by

$T_a = 1/\lambda$

** To calculate the number of radioactive atoms and the activity of the sample:-*

In each atomic weight of any element there is constant number of atoms which is called Avogadro number is equal to [(6.02×10^{23}) atoms/ Aw]. This means **(1 gm contain 6.02×10^{23} atoms/Aw).**

Making a preciseدقيق prediction of when an individual nucleus will decay is not possible; however, radioactive decay is governed by statistics, so it is very easy to predict the decay pattern of a large number of radioactive nuclei. The rate at which nuclei decay is proportional to N, the number of nuclei there are:

$$\boldsymbol{Decay\ Rate}: \boldsymbol{A = |-\frac{dN}{dt}| = \lambda N}$$

Whenever حينما the rate at which something occurs is proportional to the number of objectsاجسام, the number of objects will follow an exponential decay.

Example:

Calculate the number of radioactive atoms in 2 grams of ^{131}I if 10% of the sample contain stable atoms.

Number of radioactive atoms=(6.02×10^{23}/131 ×2gm×90/100)

(number of atoms in 1 gram)

(because 10% is stable ∴ unstable 100-10 = 90)

Example:

A person has been injected by 3mg of ^{131}I with a physical half – life

($T_{1/2}$)$_{Phy.}$= 8 days calculate :

1. The number of radioactive atoms after 3 days if the injected amount has a 2% of the stable atoms (i .e = 98% of radioactive atoms) ?

2. The mean life of this radioactive atoms?

3. The activity of the injected dose (A_o)?

Unit of Radioactivity

1. Curie $C_i = 3.7 \times 10^{10}$ disintegration / sec (This number represent the radioactivity of 1 gram of radium).

The Curie is a large quantity for nuclear medicine.

mill curie (mci) = 10^{-3} C_i .

micro curie (μci) = 10^{-6} C_i .

2. International System (SI)

unit of radioactivity is the Becquerel (Bq) = 1 disintegration / sec

(is small unit)

(KBq = 10^3 disintegration / sec)

(MBq = 10^6 disintegration / sec)

So, [1 C*i* = 3.7×10^{10} Bq]

**** There are over 1000 kwon radionuclide ,most man made .***

Iodine *has 15 known radioisotopes(**131I,123 I**) ,* ***carbon*** *has two stable isotope(^{12}C,^{13}C),and several radioisotopes(**^{11}C,^{14}C,^{15}C**), while* ***hydrogen*** *has one isotope, tritium(**^{3}H**).*

Groups of isotopes according to their uses:

1. Research Radionuclide:

Each isotopes in this group should have low energy and low penetration such as **(^{3}H give β and ^{14}C give β)** Since, ***β -particles are not very penetration and have low energies .***

2. Diagnosticتشخيص Radionuclide:

has high penetration and ***enough physical half*** – life (To cover the test time) .Such as **^{99m}Tc , ^{32}p)** are mostly γ-ray emitters enough physical half life for diagnosis test or β emitter of enough depth and **$T_{1/2}$).**

3. Therapeutic Radionuclide:

has high energy to destroy cancer cells and enough half life time (enough to cover many cells cycles)

*The most useful radionuclide for nuclear medicine are those emit ***γ-ray. since γ-ray are very penetrating***. A gamma-emitting radioactive element inside body can be detected outside the body.

* Radiation destroys the chemical bonds of DNA Generally , cells which have more divisions are more effected by radiation especially .

Radiation Detectors :

1. Geiger – Mueller Counter (G . M . counter)

A. Does not distinguish between large and small amount of ionization . Then it is convenient for use in radiation protection.

B. Since , it is in efficient for detecting γ – rays , then it is of little use in clinical nuclear medicine**.**

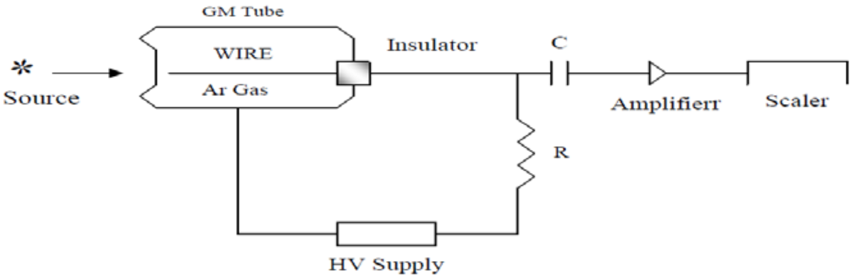


Fig.: Schematic diagram of the G-M tube and the associated electronics)

2. Scintillation detector = PMTs + Crystal of NaI(Tl)

A. ***Photomultiplier tube (PMT)*** **:**

It is sensitive for detecting even a weak flash of light and estimate the amount of light .

**** (Most PMTs have 10 dynodes , so that the electron multiplication of 105 to 106 times occurs from the photo cathode to the anode.***

B. ***NaI(Tl) crystal 1cm thick detector are about 2000 times more dense than the gas used in GM detector , and they are quite efficient for detecting γ – rays .***

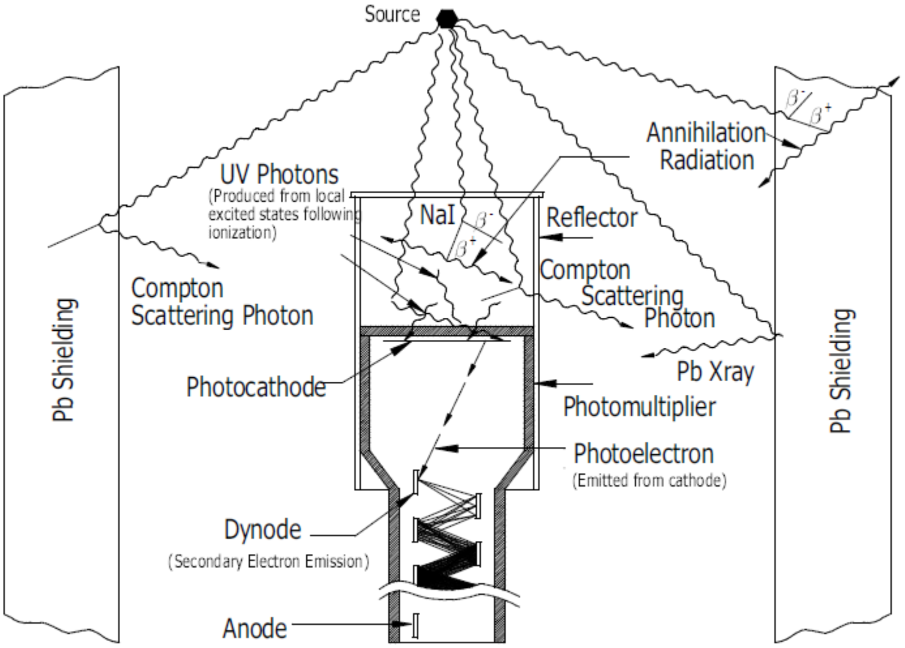


Figure: Schematic of a NaI detector and source showing various gamma ray interactions.

3. Solid State Detector :

widely used in nuclear physical research , because: they have better resolution than NaI(Tl) their disadvantages are**:-**

A. ***They are not available in large size to be used in diagnosis.***

B. ***They are much more expensive than scintillation detector.***

**** But it is very efficient to detect γ – ray in low energy.***

Health Effects of Exposure to Radiation

Exposure to high levels of radiation is known to cause cancer and, at very high levels, radiation poisoning and even death. But the effects on human health from very low doses of radiation—such as the doses from background radiation—are extremely hard to determine because there are so many other factors that can mask or distort the effects of radiation. For example, if we compare people exposed to high radon levels to cigarette smokers, the latter group is much more likely to develop lung cancer than nonsmokers. Lifestyle اسلوب حياتهم choices, geographic locations, and individual sensitivities are difficult to account for when trying to understand the health effects of background radiation

Biological Effect of Ionizing Radiation:

1. genetic effect

This affects the reproductive cells when it is irradiated, and affect later generations. Therefore, it's effect is specially on the ovaries in female and testes in male.

This effect is depend on:

1. Type of radiation.
2. amount of radiation.
3. individual age.

2. Somatic effect:

This affect on the individual directly after the exposure; and these effects are:

1. Reddening احمرار of the skin.
2. loss of hair.
3. stiffening تصلب "fibrosis" of the lung.
4. Induction of cataracts عتمة in the eyes.
5. Ulceration تقرح.
6. carcinogenesis التسرطن, induction of cancer.
7. formation of holes "fistulas" in tissues.

This effect is depend on **:**

1. Amount of radiation.
2. The part of the body irradiated.
3. Age of the patient.

Recommended Maximum Permissible Doses (MPD) for radiation workers and the general population, excluding intentional medical exposure.

1. *Thyroid Scan*مسح الغده الدرقية.

Thyroid uses Iodine in the production of hormones that control the metabolic rate of the body .

A. Person with underactive thyroid (hypothyroid function) will take up less Iodine than a person with normal thyroid function (Euthyroid)

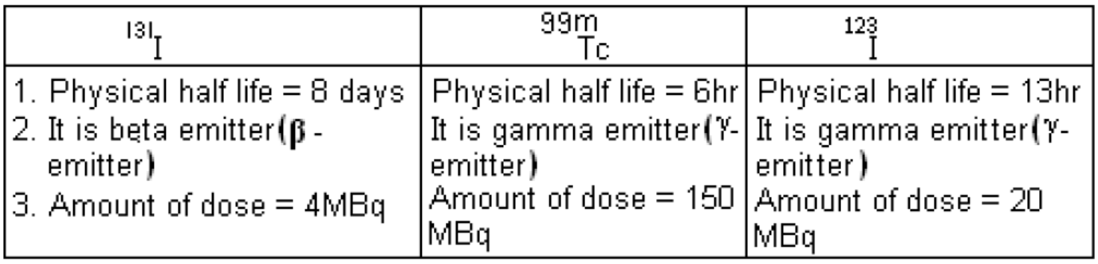
B. Person with overactive thyroid (hyper thyroid) will take up more than normal .

So,

Euthyroid up take 10 – 40% (averag 20%).

Hyper thyroid uptake > 40% .

But for up take less than 10% may be hypothyroid.



^{131}I	^{99m}Tc	^{123}I
1. Physical half life = 8 days 2. It is beta emitter(β - emitter) 3. Amount of dose = 4MBq	Physical half life = 6hr It is gamma emitter(γ- emitter) Amount of dose = 150 MBq	Physical half life = 13hr It is gamma emitter(γ- emitter) Amount of dose = 20 MBq

1. **^{99m}Tc** is much preffered than **^{131} I** because of it is less danger . **^{99m}Tc** has shorter half life and **^{99m}Tc** is γ-ray emitter while **^{131}I** in β emitter.

ا**2.** **^{123}I** is much preferred than **^{99m}Tc** because the amount of dose of **^{123}I** is less than the amount of **^{99m}Tc** and **^{123}I** is not need to chemical material ,but **^{99m}Tc** need to it.

2-Liver Scan:

1. A does about **200 MBq of ^{99m}Tc** labeled sulfur colloid with particles 0.5μm in diameter is injected into vein.

2. The image will obtained after 10min.

Sources of Radioactivity for Nuclear Medicine

3. Normal liver tissue will absorbed the radioactive particles from the blood .

4. While a tumor in the liver will not and appears on the scan as an area of reduced radioactivity.

3-Brain Scan:

1. This test is done by **500MBq of ^{99m}Tc** injected into the blood.

2. After (1 – 2) hr four image a front , back left and right sides of the head are taken , to determine the location and size and shape of tumor .

3. Normal brain tissue will not , or less absorbed the radioactivity particles.

4. While , a tumor tissue will absorbed the radioactivity particles.

This done by:100MBq of lumpyمتكتل **^{99m}Tc labeled albumin** is injected into a vein . This material travels to the heart and then to the lung .

A scan Image taken immediately after the injection shows radioactivity Where the functioning capillaries are located and little radioactivity in the part of the lung is blocked.

Lung Ventilation imaging (air):

This done by use of radioactivity gas such as **Xenon ^{133}Xe** ($T_{1/2}$ = 5.3 days) or **^{15}O** (1 – 2 min) . Both the distribution of radioactivity and the length of time it remain in a given volume to give diagnostic information.

What is the difference between radiation and radioactivity?

A **radioactive** atom is unstable because it contains extra energy, or an unbalanced number of particles, in its nucleus. When this atom ‘decays’ to a more stable atom, it releases the extra energy and/or particles as ionising **radiation**

How is ionising radiation different from other types of radiation?

Ionising radiation can eject electrons out of atoms (thereby **ionising** them), either by direct interaction with the atoms or by other methods. Alpha and beta particles, as well as X-rays and gamma rays, are examples of directly-ionising radiation, while neutrons cause ionisation by indirect processes

Lung perfusion Imaging to blood

Is there more than one kind of ionising radiation?

Yes. In addition to X-rays, three are common. They are called **alpha (α), beta (β)** and **gamma (γ) radiation**. Alpha particles (helium nuclei consisting of two protons and two neutrons) may be stopped completely by a sheet of paper, beta particles (high-speed electrons) can be stopped by perspex, while gamma rays (like X-rays, but with a shorter wavelength) may need lead or concrete to efficiently stop them - but can be stopped by any material providing there is enough of it. Other less common types of ionising radiation also exist.

If ionising radiation does not make things radioactive, how do items become radioactive in a reactor?

In a reactor there are trillions of free nuclear particles called neutrons. When absorbed by a material they may convert stable isotopes into unstable isotopes and thereby make the material radioactive (i.e. the unstable isotopes will emit their own radiation). This process is how medical radioisotopes are made in the OPAL multipurpose reactor.

How are radiation doses measured?

When trying to measure radiation there are two separate aspects to consider: radiation activity, and radiation exposure. **Activity** refers to how much radiation (in the form of particles or photons) is being emitted by a source, while **exposure** measures the effects of that radiation on anything that absorbs it.

Radiation activity is measured in an international unit called a **Becquerel (Bq)**, where 1 Bq corresponds to one particle or photon of radiation emitted per second.

Radiation exposure can be measured in three ways:

- **Absorbed dose**, which is the energy that a radiation source would deposit in one kilogram of a substance. Absorbed dose is measured in an international unit called the **Gray (Gy)**, where 1 Gy corresponds to one joule of energy per kilogram.
- **Equivalent dose**, which relates the absorbed dose in human tissue to the effective biological damage the radiation causes. Equivalent dose takes into account the fact that different forms of radiation have different biological effects, even when the amount of absorbed dose is the same—some forms of radiation are more damaging than others. Equivalent dose is obtained by multiplying absorbed dose by a radiation weighting factor that corresponds to the type of radiation absorbed. It is measured in a unit called the **Sievert (Sv)**.

- **Effective dose**, which takes into account that different parts of the body react differently to radiation exposure—some organs are more sensitive to radiation than others. Effective dose is obtained by multiplying equivalent dose by a tissue weighting factor that corresponds to the type of tissue exposed to radiation. If more than one organ is exposed to radiation, then all effective doses to all exposed organs are added together to obtain an overall effective dose. Effective dose is also measured using the **Sievert (Sv)**.

The Sievert is quite a large unit for measuring radiation - a dose of 1 Sv in a short time will cause acute radiation sickness. For describing normal radiation exposure and protection levels it is common to use smaller units such as **microSieverts (µSv)**, or millionths of a Sievert, where

1,000,000 µSv = 1 Sv.

Radiation is often measured as a dose over a specific period of time, known as the **dose rate**. For example, the typical dose rate from natural background radiation in Australia is 1,500 to 2,000 **µSv per year**, or equivalently, 4 to 5 **µSv per day**. The actual exposure received depends on both the dose rate and the exposure time.